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Heat Exchanger Expert System Logic

R. Cormier

Radio Frequency and Microwave Subsystems Section

This article describes the reduction of the operation and fault diagnostics of a DSN heat exchanger to a rule base by the application of propositional calculus to a set of logic statements. The value of this approach lies in the ease of converting the logic and subsequently implementing it on a computer as an "expert system." The rule base was written in Process Intelligent Control (PICON) software.

I. Introduction

The application of formal systems analysis and propositional calculus has great value in the design of an "expert system" rule base, where the need is to model knowledge. Propositional calculus is a formal logic system from which conclusions are deduced independent of the structure of the propositions. The conclusions follow uniquely from the truth or falsity of the propositions. Once a knowledge base has been converted to propositions, assuming it has been done correctly, the process of deduction cannot lead to contradictions or to invalid conclusions. One of the consequences is that, given an appropriate model, every deduction is a tautology. A description of formal systems and propositional calculus can be found in [1]. The breadboard heat exchanger expert system is described in [2].

The task described in this article involved the conversion of the controls and operation of a DSN heat exchanger to a set of logic statements for an "expert system" computer operating system [2]. The heat exchanger elements and the sensors that were converted to logic statements are listed in Table 1. A flow diagram (Fig. 1) indicates the position of the sensors in the piping. The electrical schematic is shown in Fig. 2.

The controls and operation were first described in terms of hardware for all conditions of service. For example, the heat exchanger has dual pumps which are fully redundant. The failure of one pump does not affect the capability of the heat exchanger to cool the transmitter, except for the reliability factor. Two fans are provided, but these are only partially redundant. Under certain conditions, both fans are required. In addition, a number of other failures can be tolerated provided the heat exchanger is operated locally. The Pumps Alternating command can be bypassed with a local switch, in which case both pumps may be operated simultaneously. All of these conditions were described and incorporated in the rule base, as the expert system needed the capability to distinguish between and not be confused by these alternatives.

II. Operational Logic Statements

The word description of the heat exchanger operation was then converted to logic statements or schemata. The symbols used for the elements are defined in Table 1. The operand symbols are defined in the Appendix.

For simplicity, the limits in the summations have been omitted, but are equal to those of Eq. (A-3). After considerable algebra, the functions in Eq. (A-6) reduce to

$$f_{11} = \frac{(N_s - |\ell|) \cos \left[\frac{\pi}{N_s} \ell \right]}{\left[\sin \left(\frac{\pi}{2N_s} \right) \right]^2} \quad 0 \leq |\ell| \leq N_s \quad (\text{A-9})$$

$$f_{12} = \frac{\sin \left(\frac{\pi |\ell|}{N_s} \right)}{\sin \left(\frac{\pi}{N_s} \right)} \left[\frac{1}{\sin \left(\frac{\pi}{2N_s} \right)} \right]^2 \quad 0 \leq |\ell| \leq N_s \quad (\text{A-10})$$

$$f_{21} = (N_s - |\ell|)^2 \quad 0 \leq |\ell| \leq N_s \quad (\text{A-11})$$

$$f_{22} = \left[\frac{\sin \left(\frac{\pi \ell}{N_s} \right)}{\sin \left(\frac{\pi}{N_s} \right)} \right]^2 \quad 0 \leq |\ell| \leq N_s \quad (\text{A-12})$$

After collecting the terms in Eqs. (A-9)–(A-12) and using Eq. (A-6), the correlation function shown in the main text is obtained.

The heat exchanger is operational whenever it is providing cooling for the transmitter. Coolant must be flowing and heat must be removed from the coolant. This implies that at least one pump and at least one fan are operating, with the second fan available if required for additional heat transfer. The fan operation depends on the coolant temperature at the output of the core. The two conditions are (a) for a coolant temperature $<120^{\circ}\text{F}$; and (b) for a coolant temperature $>110^{\circ}\text{F}$.

Let

a denote condition a is true

b denote condition b is true

\bar{a} denote condition a is false

\bar{b} denote condition b is false.

Given this notation, it can be stated that the heat exchanger is operational when

$$v \vee w : \bar{a} \rightarrow xy : \bar{b} \rightarrow .xy \vee \bar{xy} : ab \rightarrow .x \vee y$$

The use of dots in the above statement indicates grouping as referenced in the appendix. This states that (1) for the heat exchanger to be operational, at least one pump (v or w) is on; and (2) if the coolant temperature is not less than 120°F , then two fans (x and y) are operating, if the coolant temperature is not greater than 110°F , then at least one fan is on but not both, and if the coolant temperature is between 110°F and 120°F , then either fan 1 is on or fan 2 is on or both. The advantage of schemata can be appreciated when it is desired to check the consequences of a statement like the one above. The heat exchanger is not operational when the negative of the above is made by the use of DeMorgan's law:

$$\bar{v}\bar{w} \vee : \bar{a} . \bar{x} \vee \bar{y} : \bar{b} : \bar{x} \vee y . x : \bar{y} : \bar{v} ab \bar{xy}$$

This states that for the heat exchanger to be not operational, both pumps (v and w) are off or the coolant temperature is not less than 120°F , and either fan 1 (x) is off or fan 2 (y) is off; or the coolant temperature is not greater than 110°F and either fan 1 is off or fan 2 is on, or vice versa; or the coolant temperature is between 110°F and 120°F and both fans are off.

In the process of taking the inverse, the "if-then" statements of the original schema were eliminated and only conjunctions and alternations remained. This form is known as the "alternative normal form." Using this form, it is simple to remove inconsistencies. If the schema was found to be valid, i.e., true under all conditions of its terms, then this would mean that the original schema before inversion was incon-

sistent. This is a useful check, and errors were found and eliminated by this method. Although the above may be logically true, from a practical point of view the heat exchanger would not be considered not operational if both fans were on with a coolant temperature of less than 110°F . In this case, the failure does not degrade the cooling capacity of the heat exchanger. This is an example of the necessity of analyzing each schema and its inverse. It is not always obvious what the consequences are, even for rather simple definitions.

Several assumptions and simplifications were made. It was assumed that the heat exchanger is commanded on either from the transmitter or from the local panel and that prime power is available. It was also assumed that with one pump operating, 20 gpm of coolant with a pressure differential of 125 psi is being supplied. Similarly, it was assumed that the operation of the fans moves a quantity of air adequate to maintain the coolant exhaust temperature at the transmitter output at less than 70°C . Obviously, however, these conditions are not always necessarily true; they are also addressed in Section III.

The heat exchanger is controlled from a three-position switch located on a panel on the heat exchanger. In the Local position (c_l), power is applied; in the Off position (c_o), no power is applied; and in the Remote position (c_r), power is applied if the transmitter control power (p_1) is on. With respect to the REMOTE/OFF/LOCAL switch S2, and again using the notation of the appendix, the heat exchanger is operational when

$$c_r p_1 \vee c_l \leftarrow \rightarrow .v \vee w . x \vee y$$

Associated with the pumps are time delay relays TDR1 and TDR2 and pressure switches S4 and S5. When the heat exchanger is turned on, the time delay relays inhibit the pressure switches during the time required for the motors to reach operating speed. If a pump does not deliver operating coolant pressure by the time the time delay relay has timed out, that pump will be turned off and the other backup pump will be turned on. This provides redundancy in case of a pump failure. The time delays of relays TDR1 and TDR2 are designated r_1 and r_2 , and the functions of pressure switches S4 and S5 are designated s_4 and s_5 .

In addition, there are two alternating relays for the pumps and the fans K9 and K14, respectively. To simplify which pump and which fan are being turned on at any given time, the times are designated t_1 for pump 1 and fan 1, and t_2 for pump 2 and fan 2. After t_2 , the time starts at t_1 again.

The hardware conditions for the operation of pump 1 are as follows:

- (1) The control circuit breaker (b_c) is closed.

- (2) The main circuit breaker (b_7) is closed.
- (3) The pump 1 circuit breaker (b_1) is closed.
- (4) The pump 1 contactor (k_1) is closed.
- (5) The tank low-level switch (s_3) is closed.
- (6) The 480-Vac three-phase power (p_2) is available.
- (7) The pump 1 thermal overload (o_1) is closed.

Similarly, for pump 2:

- (1) The control circuit breaker (b_6) is closed.
- (2) The main circuit breaker (b_7) is closed.
- (3) The pump 2 circuit breaker (b_2) is closed.
- (4) The pump 2 contactor (k_2) is closed.
- (5) The tank low-level switch (s_3) is closed.
- (6) The 480-Vac three-phase power (p_2) is available.
- (7) The pump 2 thermal overload (o_2) is closed.

The control switch is in either the Local or the Remote position. If it is in Remote, the 28-Vdc control power (p_1) is on from the transmitter and the tank low-pressure cutoff switch (s_1) is closed. In addition, either the alternating relay is in Pump 1 position (and when pump 1 was turned on, it reached a pressure of 60 psig before the pump 1 time delay relay closed) or pump 2 was turned on (and the alternating relay for pump 2 timed out before the pressure reached 60 psig or the pressure dropped while pump 2 was operating). This can be written in a condensed form using the dot notation in the appendix (with multiple dots representing a greater break) as follows:

For pump 1:

$$r_1 s_4 t_1 V \cdot t_2 \cdot \bar{r}_2 V \bar{s}_5 : c_1 V c_r s_1 p_1 \cdot b_6 b_7 p_2 b_1 k_1 s_3 o_1 \\ \therefore \longleftrightarrow v$$

Similarly, with appropriate change of components, pump 2 operation is:

$$r_2 s_5 t_2 V \cdot t_1 \cdot \bar{r}_1 V \bar{s}_4 : c_1 V c_r s_1 p_1 \cdot b_6 b_7 p_2 b_2 k_2 s_3 o_2 \\ \therefore \longleftrightarrow w$$

There are conditions when both pumps may be operating together. This involves either the use of the critical command (c_c) or the closure of the alternating relay disable switch (s_{10}). For pump 1 and pump 2 both operating,

$$c_1 V c_r s_1 p_1 \cdot c_c V s_{10} \cdot b_6 b_7 p_2 b_1 b_2 k_1 k_2 s_3 o_1 o_2 \\ \therefore \longleftrightarrow w v$$

The conditions for the fans are similar but not identical to those for the pumps. The appropriate circuit breakers, relays, overloads, switches, and voltages are required. The difference is that the fans are not fully redundant and do not back each other up. In addition, the coolant level, the alternating bypass switch, and the pressure cutoff switches are not in the fan circuit. A temperature switch monitors the coolant, and when the coolant temperature is greater than 110°F at the output to the coil, the second fan is commanded on.

The hardware conditions for the operation of fan 1 are:

- (1) The control circuit breaker (b_6) is closed.
- (2) The main circuit breaker (b_7) is closed.
- (3) The fan 1 circuit breaker (b_3) is closed.
- (4) The fan 1 contactor (k_3) is closed.
- (5) The 480-Vac three-phase power (p_2) is available.
- (6) The fan 1 thermal overload (o_3) is closed.

Similarly, for fan 2:

- (1) The control circuit breaker (b_6) is closed.
- (2) The main circuit breaker (b_7) is closed.
- (3) The fan 2 circuit breaker (b_4) is closed.
- (4) The fan 2 contactor (k_4) is closed.
- (5) The 480-Vac three-phase power (p_2) is available.
- (6) The fan 2 thermal overload (o_4) is closed.

For fan 1:

$$t_2 V t_1 k_{15} \cdot c_1 V c_r s_1 p_1 \cdot b_7 b_3 b_6 p_2 k_3 o_3 : \longleftrightarrow y$$

For fan 2:

$$t_1 V t_2 k_{15} \cdot c_1 V c_r s_1 p_1 \cdot b_7 b_4 b_6 p_2 k_4 o_4 : \longleftrightarrow x$$

For fan 1 and fan 2:

$$o_3 o_4 b_7 b_4 b_3 b_6 p_2 k_3 k_4 k_{15} \cdot c_1 V c_r s_1 p_1 : \longleftrightarrow x y$$

At this point, schemata have been written to describe the operation of the pumps and the fans. These are true when the antecedent and the consequent are both true or both false. The

schema is false when the antecedent and the consequent are not both true or false. Since the operation of the pumps or fans is monitored independent of the hardware used for the antecedent, a false schema indicates a problem with either the sensor or the data collection. If the biconditional is broken into two conditionals and each is tested independently, the conditionals may provide different information. This is the case with the pumps, and this procedure can be used as a diagnostic.

Part of knowing the operational status lies in keeping track of the various time durations. How long has the expert system been monitoring? How long has the heat exchanger been on? How many times has the heat exchanger been turned on and off? Other clocks were added as required. Time clock parameters are the following:

t_l = elapsed time since PICON has been on line monitoring

t_r = continuous accumulated time since the heat exchanger was turned on

t_t = continuous accumulated time duration since the transmitter was turned on

t_c = number of times the heat exchanger has been turned on

III. Heat Exchanger Diagnostics Description

The next task was to list all components (least replaceable units) and failure modes. It was then necessary to identify the symptoms and the response of the sensors to each. After describing the various possible failures, the propositional logic statements were written using the available sensors. For this purpose, the phrase "heat exchanger on" was taken to mean that one pump and one fan were operating. A sensor was available for the coolant flow, but the sensor for the air flow proved to be so noisy as to be unusable. The fan rotation sensor was inoperative due to burned-out lamps. Consequently, no direct means of monitoring air flow was available, so the fan motor prime power loading was used instead for the rules. A sensor for the position of the local control switch S2 was not available, although such a sensor would have simplified the rules.

The heat exchanger is required to provide liquid cooling for the transmitter. In order to do this, it must deliver at least 20 gpm with a pressure differential of at least 125 psid. The coolant temperature is not to exceed 70°C. The head of the transmitter load from the output of the heat exchanger is 125 ft. Coolant purity is to be maintained with a resistivity of not less than 2 megohms per centimeter. These are the most critical requirements. Failure to meet these requirements may

be due either to parts failure in the heat exchanger or to failures in the transmitter or prime power; this project was limited in scope to the heat exchanger. External failures were identified whenever possible, but no procedures were developed to isolate such faults.

The diagnostics began with the heat exchanger off: In the Off state, is the heat exchanger available for operation? It is not possible to answer this on the basis of sufficient conditions, but it is possible to conclude some necessary conditions for the heat exchanger to be turned on. The "H.E. not available" rule defines the conditions that prevent the heat exchanger from being turned on. Fault localization depends on sensors. It is always possible that a sensor has failed and the equipment is nevertheless operational. Unfortunately, it is not easy to isolate sensor failures from equipment failures; only through gross sensor error or sensor redundancy can some sensor failures be isolated. This area has not been thoroughly analyzed, and rules have not been developed except for a few obvious ones.

The "H.E. not available" rule was then broken up into various rules that identified faults either to a component or, if that was not possible, to an area. For example, if a circuit breaker has tripped, the possibilities are endless. Reasonable and probable considerations must be used in the deductive process. The tripped circuit breaker could be the result of sabotage, but this is neither reasonable nor probable. The following basic assumptions were made:

- (1) Wiring has a negligible probability of failure.
- (2) Multiple failures of independent components involving the joint probability of two failures occurring simultaneously are negligible.
- (3) Problems that cannot be isolated to a component will require a technician to troubleshoot the fault with the use of test equipment and procedures.

For the category "H.E. not available," the choice of sensors was an adequate compromise. With the sensors available, it was not possible to identify the failure of a fuse in the control circuit. Sensors should be relocated in the future to identify this potential failure.

The next category is "H.E. available." In this category, warnings are included. In general, if the heat exchanger is capable of providing cooling for full power operation with no failures, no reporting is desired. If the heat exchanger is capable of providing cooling even though failures or potential failures exist, then that information is reported. The basic schema was deduced as an exclusive-OR of these two conditions, namely, "H.E. not available" and "no failures."

Some faults are detected only with the heat exchanger on. If the heat exchanger is not capable of cooling the transmitter as required, the condition is called "H.E. not working." Note that the conditions "H.E. not working" and "H.E. not available" differ only in that the heat exchanger must be commanded to operate to detect "H.E. not working" conditions. In the "H.E. not available" category are faults which are detected whether the heat exchanger is commanded on or off.

An interlock fault is indicated when a switch sensor located in the transmitter indicates a fault. A corresponding analog sensor provides the actual value for each interlock. Since these are independent of each other, small differences in calibration can be expected. The heat exchanger may be operating correctly and an interlock fault may indicate a problem in the transmitter.

When an interlock is activated, the transmitter beam power is turned off, reducing the heat load immediately and decreasing the coolant temperature drastically. The values of flow rate and temperature just before the activation of an interlock comprise very useful diagnostic information.

The failure of the pumps or the fans to cycle properly is an indication of equipment failure. Each time the heat exchanger is turned off and then turned on, the pumps and fans are alternately switched. A failure to switch indicates a failure that, if not repaired, will lead to a heat exchanger failure. In addition, the reliability factor is degraded by the loss of redundancy.

IV. Diagnostics Logic Statements

The next step in the task was to convert the diagnostic description to maintenance logic that is understood by a computer. One simplification made was that any fan failure is a heat exchanger failure.

A. "H.E. Not Available" Rules

In terms of hardware sensors:

- (1) If both pump thermal overloads (sensors $d_{6,100}$ and $d_{6,200}$) are open, or
- (2) If both pump circuit breakers (sensors $d_{3,80}$ and $d_{3,100}$) are open, or
- (3) If one pump circuit breaker and the other pump thermal overload are open, or
- (4) If either fan circuit breaker (sensors $d_{3,200}$ and $d_{3,400}$) is open, or
- (5) If either fan thermal overload (sensors $d_{6,400}$ and $d_{6,800}$) is open, or

- (6) If the control circuit breaker (sensor $d_{3,1}$) is open, or
- (7) If the main circuit breaker ($d_{3,8000}$) is open, or
- (8) If the phase-sensitive relay (sensor $d_{3,40}$) is open, or
- (9) If the 120-Vac control power (sensor $d_{6,8000}$) is not present, or
- (10) If low reservoir level switch ($d_{6,10}$) is open, or
- (11) If low nitrogen pressure switch ($d_{6,20}$) is open,

then the sensors indicate that if the heat exchanger were to be asked to operate, it would not be available to cool the transmitter. Indeed, if it *did* turn on, then the sensors or the data link have failed. This is written as:

$$\bar{d}_{3,1} \vee \bar{d}_{3,40} \vee \bar{d}_{6,10} \vee \bar{d}_{6,20} \vee \bar{d}_{3,80} \bar{d}_{6,200} \vee \bar{d}_{3,100} \bar{d}_{6,100} \vee \bar{d}_{6,800} \vee \bar{d}_{6,400} \vee \bar{d}_{3,80} \bar{d}_{3,100} \vee \bar{d}_{3,200} \vee \bar{d}_{3,400} \vee \bar{d}_{6,100} \bar{d}_{6,200} \vee \bar{d}_{3,8000} \vee \bar{d}_{6,8000} \rightarrow \text{Sensors indicate that the heat exchanger is not available}$$

where $d_{i,j}$ indicates a normal value from the sensor $D_{i,j}$ and $\bar{d}_{i,j}$ indicates a fault value from the sensor $D_{i,j}$.

When the rule "H.E. not available" is activated, the following sensor information is useful in localizing faults:

$$\bar{d}_{3,80} \bar{d}_{6,200} \vee \bar{d}_{3,100} \bar{d}_{6,100} \vee \bar{d}_{3,80} \bar{d}_{3,100} \vee \bar{d}_{6,100} \bar{d}_{6,200} \rightarrow \text{Sensors indicate that both pumps are not operational due to either tripped circuit breakers or tripped overloads.}$$

This can be divided further:

- (1) $d_{3,80} d_{3,100} \bar{d}_{6,100} d_{6,200} \rightarrow$ Sensors indicate a short in pump 1.
- (2) $\bar{d}_{3,80} d_{3,100} d_{6,100} d_{6,200} \rightarrow$ Sensors indicate a short circuit in primary wiring to pump 1.
- (3) $d_{3,80} d_{3,100} d_{6,100} \bar{d}_{6,200} \rightarrow$ Sensors indicate a short in pump 2.
- (4) $d_{3,80} \bar{d}_{3,100} d_{6,100} d_{6,200} \rightarrow$ Sensors indicate a short circuit in primary wiring to pump 2.
- (5) $\bar{d}_{6,10} \bar{a}_{1,1} \rightarrow$ Low reservoir level sensor indicates the heat exchanger is not available. Add coolant and check for leaks. (Note that an analog sensor always has a value because for a signal of zero a current of 4 mA is the output. A sensor failure or data link failure is detected by not receiving the 4 mA.)

- (6) $\bar{d}_{6,10} a_{1,1} \rightarrow$ Low reservoir level signal is not available.
- (7) $\bar{d}_{6,20} \bar{a}_{1,2000} \rightarrow$ Low nitrogen pressure indicates the heat exchanger is not available. Add nitrogen.
- (8) $\bar{d}_{6,20} a_{1,2000} \rightarrow$ Low-pressure cutoff switch signal is not available.

The next set of diagnostics involves control power:

- (1) $\bar{d}_{3,1} \rightarrow \bar{d}_{6,8000}$
- (2) $\bar{d}_{3,1} V \bar{d}_{6,8000} \cdot d_{3,8000} d_{3,40} \rightarrow$ Sensors indicate a heat exchanger control short circuit.
- (3) $\bar{d}_{3,40} V \bar{d}_{6,8000} \cdot d_{3,1} \rightarrow$ Sensors indicate a heat exchanger three-phase power fault.
- (4) $d_{3,200} d_{3,400} \bar{d}_{6,400} d_{6,800} \rightarrow$ Sensors indicate a short in fan 1.
- (5) $\bar{d}_{3,200} d_{3,400} d_{6,400} d_{6,800} \rightarrow$ Sensors indicate a short circuit in primary wiring to fan 1.
- (6) $d_{3,200} d_{3,400} d_{6,400} \bar{d}_{6,800} \rightarrow$ Sensors indicate a short in fan 2.
- (7) $d_{3,200} \bar{d}_{3,400} d_{6,400} d_{6,800} \rightarrow$ Sensors indicate a short circuit in primary wiring to fan 2.

B. "H.E. Available" Rules

The heat exchanger may be in need of maintenance and still be capable of cooling the transmitter. This condition is called "H.E. available." The following schema can be deduced from the "H.E. not available" rule:

$$\begin{aligned} &\bar{d}_{3,80} d_{6,200} V \bar{d}_{3,100} d_{6,100} V \bar{d}_{6,100} d_{6,200} V \\ &\bar{d}_{3,80} d_{3,100} V \bar{d}_{3,100} d_{3,80} V \bar{d}_{6,200} d_{6,100} V \\ &\bar{d}_{6,100} d_{3,100} V \bar{d}_{6,200} d_{3,80} \cdot \rightarrow \text{The heat} \\ &\text{exchanger is available for operation, but mainte-} \\ &\text{nance is to be performed as soon as possible.} \end{aligned}$$

When the "H.E. available" rule is activated, the following sensor information is useful in localizing faults. Included in this category are the warnings that require attention of maintenance personnel but still allow operation to continue:

- (1) $(a_{1,2000} < 30 \text{ psig}) d_{6,20} \rightarrow$ Add nitrogen to the heat exchanger tank.
- (2) $\bar{a}_{1,1} d_{6,10} \rightarrow$ Add coolant to the tank. Check for leaks in the heat exchanger and the transmitter cooling pipe assemblies.

Some faults are detected only with the heat exchanger on. If the heat exchanger is on and not capable of cooling the

transmitter as required, the condition is called "H.E. not working." Note that the condition "H.E. not working" and "H.E. not available" differ only by the ON/OFF command. All "H.E. not available" conditions are also included in the "H.E. not working" category, as these are not mutually exclusive. Only conditions that would not be detected with the heat exchanger off are listed below:

- (1) $\{(a_{1,800} - a_{1,2000}) < 125 \text{ psig}\} \rightarrow \bar{a}_{1,800}$
- (2) $\bar{a}_{1,20} \bar{a}_{1,800} (a_{1,20} > 2 \text{ gpm}) d_{6,4} \rightarrow$ The heat exchanger output flow is less than 20 gpm with a pressure of less than 125 psid as indicated by coolant flow sensors. Replace operating main pump.
- (3) $d_{6,4} \bar{d}_{6,2} d_{6,10} d_{6,20} \rightarrow$ Relay K7 defective or heat exchanger control switch S2 in the off position. The heat exchanger may be operated locally until K7 is replaced.
- (4) $\bar{a}_{2,4} \bar{a}_{2,8} d_{6,10} d_{6,20} d_{6,4} \rightarrow$ Fans are not operating properly. Both fans are off.
- (5) $\bar{a}_{1,40} a_{1,20} \cdot a_{2,4} \bar{a}_{2,8} V \bar{a}_{2,4} a_{2,8} \rightarrow$ Warning! Coolant temperature greater than 110°F and both fans are not on.
- (6) $\bar{d}_{6,1} a_{1,20} \rightarrow$ There is no flow in the purity loop. Replace the submicrometer filter (item 34 of the piping diagram).
- (7) $\bar{a}_{1,4} a_{1,20} (t_r > 10 \text{ min}) \rightarrow$ Replace the purity cartridge (item 24 of the piping diagram).
- (8) $\bar{a}_{1,2} a_{1,4} a_{1,20} (t_r > 1 \text{ hr}) \rightarrow$ Main coolant loop is being contaminated. Localize the cause of contamination. Replace defective component.
- (9) $(a_{1,20} < 2 \text{ gpm}) d_{3,1} d_{3,8000} d_{6,2} d_{6,4} d_{6,10} d_{3,80} d_{3,100} d_{6,20} d_{6,100} d_{6,200} d_{6,8000} \rightarrow$ Sensors indicate a heat exchanger control open circuit.

The transmitter and heat exchanger are usually operated with the heat exchanger controlled by the transmitter. It is also possible to operate the heat exchanger from local controls. This condition is detected only when the transmitter is off and the heat exchanger is on. If both systems are on, there is no way to tell that the heat exchanger is being operated locally:

$$a_{1,20} \bar{d}_{6,4} \rightarrow \text{Heat exchanger under local control.}$$

An interlock fault is indicated when a switch sensor located in the transmitter indicates a fault. A corresponding analog sensor provides the actual value for each interlock. Since these are independent of each other, small differences in calibration can be expected. The heat exchanger may be operating cor-

rectly and an interlock fault may indicate a problem in the transmitter:

$$\bar{a}_{1,20} \bar{a}_{1,800} \cdot \bar{d}_{5,1} \vee \bar{d}_{5,2} \vee \bar{d}_{5,4} \vee \bar{d}_{5,8} \vee \bar{d}_{5,10} \vee \bar{d}_{5,20} \vee \bar{d}_{5,40} \vee \bar{d}_{5,80} : \longrightarrow \text{Interlock monitoring problem, not a heat exchanger problem.}$$

The following sensor information is useful in isolating interlock faults:

- (1) $\bar{a}_{1,20} \bar{a}_{1,800} \cdot \bar{d}_{5,1} \vee \bar{d}_{5,2} \vee \bar{d}_{5,4} \vee \bar{d}_{5,8} \vee \bar{d}_{5,10} \vee \bar{d}_{5,20} \vee \bar{d}_{5,40} \vee \bar{d}_{5,80} \longrightarrow$ Sensors indicate the cause of the interlock is the heat exchanger.
- (2) $\bar{d}_{5,1} \vee \bar{d}_{5,4} \vee \bar{d}_{5,10} \vee \bar{d}_{5,40} \longrightarrow$ Flow interlock:
Magnet flow -----
Body flow -----
Collector flow -----
RF load flow -----
- (3) $\bar{d}_{5,2} \vee \bar{d}_{5,8} \vee \bar{d}_{5,20} \vee \bar{d}_{5,80} \longrightarrow$ Temperature interlock:
Magnet temperature -----
Body temperature -----
Collector temperature -----
RF load temperature -----

The values of flow and temperature would be given where the dashed lines appear. These values provide valuable information to a maintenance technician.

A condition for the cycling is that a different pump and a different fan be turned on each time the heat exchanger is turned on. Turn-on counter t_c is incremented each time the heat exchanger is turned on.

Pumps cycling:

- (1) $\bar{d}_{3,4} \bar{d}_{3,8} \longrightarrow$ Pump 1 is on.
- (2) $\bar{d}_{3,4} d_{3,8} \longrightarrow$ Pump 2 is on.
- (3) $\bar{d}_{3,4} \bar{d}_{3,8} (t_c) \cdot \bar{d}_{3,4} d_{3,8} (t_c + 1) : \longrightarrow$ Pumps are cycling properly.
- (4) $\bar{d}_{3,4} d_{3,8} (t_c) \cdot \bar{d}_{3,4} \bar{d}_{3,8} (t_c) : \longrightarrow$ Pumps are cycling properly.
- (5) $d_{3,4} (t_c) \cdot d_{3,4} (t_c + 1) : \vee : d_{3,8} (t_c) \cdot d_{3,8} (t_c + 1) : \therefore \longrightarrow$ Pumps are not cycling properly.

Fans cycling:

- (1) $\bar{d}_{3,10} \bar{d}_{3,20} \longrightarrow$ Fan 1 is on.
- (2) $\bar{d}_{3,10} d_{3,20} \longrightarrow$ Fan 2 is on.
- (3) $\bar{d}_{3,10} \bar{d}_{3,20} (t_c) \cdot \bar{d}_{3,10} d_{3,20} (t_c + 1) : \longrightarrow$ Fans are cycling properly.
- (4) $\bar{d}_{3,10} d_{3,20} (t_c) \cdot \bar{d}_{3,10} \bar{d}_{3,20} (t_c + 1) : \longrightarrow$ Fans are cycling properly.
- (5) $d_{3,10} (t_c) \cdot d_{3,10} (t_c + 1) : \vee : d_{3,20} (t_c) \cdot d_{3,20} (t_c + 1) : \therefore \longrightarrow$ Fans are not cycling properly.

This is not an exhaustive set of rules. Additional rules should be added by maintenance personnel as experience is obtained with actual failures and repairs. Ideally, each failure should be analyzed and new rules developed to improve the capability of the expert system.

V. Other Diagnostics

Analysis of heat exchanger efficiency and trends such as reservoir level changes can be implemented. This type of information alerts maintenance personnel to possible future problems. Preventive or scheduled maintenance can correct a potential problem before an actual failure occurs.

A decreasing reservoir level indicates a leak which, if not corrected, will lead to an equipment failure. Actually, detecting the tank level is somewhat complicated. The reservoir level changes when the pumps are turned on due to the expansion of the piping caused by the increased pressure at the output of the pumps. Another factor is the expansion of metals due to temperature. These complications can be taken into account in one of two ways: the variation of each measured parameter can be found and appropriate corrections made, or the measurement can be made only at times when conditions are identical. For example, the tank level will be measured only when the pumps are off and the temperature is within defined limits.

The heat exchanger efficiency was a different problem. Deteriorating efficiency indicates future problems. Originally, it was intended to calculate the U-factors in the following manner [3]:

$$q = UA \Delta T_m$$

where

U = overall heat-transfer coefficient

A = surface area for heat transfer consistent with the definition of U

ΔT_m = suitable mean temperature difference across the heat exchanger

However, this method proved to be impractical for a number of reasons. Some of the parameters needed are difficult to measure (e.g., mass air flow); some of the sensors proved to be unreliable; some of the sensors were not available (e.g., sensors to measure specific heat of the coolant); and the heat is dissipated in other places outside the heat exchanger core. (The dissipation of heat in the long piping lines between the heat exchanger and the transmitter depends on the elements, such as rain, snow, ambient temperature, and wind.) Actually, the choice of U -factors was a bad one. A better choice would have been the Effectiveness-NTU method, defined as

$$\text{effectiveness} = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}}$$

This method has the advantage that the inlet and outlet air temperature do not have to be measured. The disadvantage of this method is the difficulty in obtaining the mass flow rate of air across the coil.

However, the problem can be reduced to a much simpler one. The heat taken out of the coolant by the coil can be measured without difficulty, and the efficiency of the heat transferred is a function of the difference in temperature between

the coolant temperature at the outlet of the coil and the air ambient temperature. The heat exchanger can be calibrated and a table of values stored for comparison. Corrections can be made for the specific heat of the coolant, air humidity, and barometric pressure. Allowing for data errors, a value of the efficiency can be used to estimate long-term degradation in cooling efficiency. The failure to measure U -factors appears to be a case of insufficient investigation of the problem during the design stage. As described above, however, a simple alternative exists that could provide the information needed by maintenance personnel.

VI. Conclusions

Based on the work carried out, the following conclusions were made:

- (1) The use of propositional logic is well suited to the development of expert maintenance systems.
- (2) The development of expert maintenance systems must involve on-site maintenance personnel.
- (3) The expert system must include not only past experience but present and future experience as well.
- (4) The initial effort need not be exhaustive, but rather should form a shell that can be expanded with new rules and new procedures. In this way it will be easily accepted by users and can be developed to reach its full potential.

References

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Table 1. Heat exchanger sensors and elements

Sensor number	Description	Definition	Statement
A-01*0001	Reservoir level transducer	>1.5 ft → a _{1,1}	
A-01*0002	Resistivity inlet purity	>2 megohms/cm ² → a _{1,2}	
A-01*0004	Resistivity outlet purity	>5 megohms/cm ² → a _{1,4}	
A-01*0008	HE core flow	a _{1,8}	
A-01*0010	HE bypass flow	a _{1,10}	
A-01*0020	HE total flow	>20 gpm → a _{1,20}	
A-01*0040	HE core outlet temperature	<112°F → a _{1,40}	
A-01*0080	HE core inlet temperature	a _{1,80}	
A-01*0100	HE assy inlet temperature	not used	
A-01*0200	Ambient air temperature	a _{1,200}	
A-01*0400	Core air flow pressure delta	not usable; too noisy	
A-01*0800	Pump outlet pressure	a _{1,800}	
A-01*1000	Core outlet pressure	a _{1,1000}	
A-01*2000	Suction inlet pressure	>15 psig → a _{1,2000}	
A-01*4000	Pump inlet temperature	not used	
A-01*8000	Heater outlet temperature	not part of DSN HE	
A-02*0001	Pump 1 motor load	not used	
A-02*0002	Pump 2 motor load	not used	
A-02*0004	Fan #1 motor load	>1200 watts → a _{2,4}	
A-02*0008	Fan #2 motor load	>1200 watts → a _{2,8}	
A-02*0010	Fan #1 speed	not reliable	
A-02*0020	Fan #2 speed	not reliable	
A-02*0040	3-way valve position	not working	
A-02*0080	Spare		
A-02*0100	HE assy outlet temperature	a _{2,100}	
A-02*0200	Heater load	not part of DSN HE	
A-02*0400	Differential pressure across main line filter	<15 psid → a _{2,400}	
D-03*0001	Auxiliary contacts on CB6	d _{3,1}	b ₆
D-03*0002	Auxiliary contacts on K5	not used	
D-03*0004	Auxiliary contacts on K1	d _{3,4}	k ₁
D-02*0008	Auxiliary contacts on K2	d _{3,8}	k ₂
D-03*0010	Auxiliary contacts on K3	d _{3,10}	k ₃
D-03*0020	Auxiliary contacts on K4	d _{3,20}	k ₄
D-03*0040	Auxiliary contacts on K6	d _{3,40}	p ₂
D-03*0080	Auxiliary contacts on CB1	d _{3,80}	b ₁
D-03*0100	Auxiliary contacts on CB2	d _{3,100}	b ₂
D-03*0200	Auxiliary contacts on CB3	d _{3,200}	b ₃
D-03*0400	Auxiliary contacts on CB4	d _{3,400}	b ₄
D-03*0800	Auxiliary contacts on CB5	not used	
D-03*1000	Auxiliary contacts on K8	not working on test HE	c _c
D-03*2000	Limit SW #1, plenum door	not used	
D-03*4000	Limit SW #2, plenum door	not used	
D-03*8000	Auxiliary contacts on CB7	d _{3,8000}	b ₇
A-04*0001	Magnet flow	>1.5 gpm → a _{4,1}	
A-04*0002	Magnet temperature	<70°C → a _{4,2}	
A-04*0004	Body flow	>1.2 gpm → a _{4,2}	
A-04*0008	Body temperature	<70°C → a _{4,4}	
A-04*0010	Collector flow	>18 gpm → a _{4,10}	
A-04*0020	Collector temperature	<70°C → a _{4,20}	
A-04*0040	RF load flow	>6 gpm → a _{4,40}	
A-04*0080	RF load temperature	<70°C → a _{4,80}	
A-04*0100	Magnet voltage	not used	
A-04*0200	Magnet current	not used	

Table 1. (contd)

Sensor number	Description	Definition	Statement
A-04*0400	Spare		
A-04*0800	Body current	not used	
A-04*1000	RF load power	not used	
A-04*2000	Spare		
A-04*4000	Beam voltage	not used	
A-04*8000	Beam current	not used	
D-05*0001	Low magnet flow interlock	d _{5,1}	
D-05*0002	High magnet temperature interlock	d _{5,2}	
D-05*0004	Low body flow interlock	d _{5,4}	
D-05*0008	High body temperature interlock	d _{5,8}	
D-05*0010	Low collector flow interlock	d _{5,10}	
D-05*0020	High collector temperature interlock	d _{5,20}	
D-05*0040	Low RF load flow interlock	d _{5,40}	
D-05*0080	High RF load temperature interlock	d _{5,80}	
D-05*0100	RF load and RF power range	not used	
D-06*0001	Purity loop flow switch	d _{6,1}	
D-06*0002	Auxiliary contacts on K7	d _{6,2}	k ₇
D-06*0004	Monitor control power across connector pins A and B	d _{6,4}	p ₁
D-06*0008	Auxiliary contacts on S8	d _{6,8}	
D-06*0010	Low reservoir level switch	d _{6,10}	s ₃
D-06*0020	Low nitrogen pressure switch	d _{6,20}	s ₁
D-06*0040	PM1 resistivity meter status	d _{6,40}	
D-06*0080	PM2 resistivity meter status	d _{6,80}	
D-06*0100	OL1 K1 thermal O/L status	d _{6,100}	o ₁
D-06*0200	OL2 K2 thermal O/L status	d _{6,200}	o ₂
D-06*0400	OL3 K3 thermal O/L status	d _{6,400}	o ₃
D-06*0800	OL4 K4 thermal O/L status	d _{6,800}	o ₄
D-06*1000	OL5 K5 thermal O/L status	not used	
D-06*2000	S4 pressure switch status	not working in test HE	s ₄
D-06*4000	S5 pressure switch status	not working in test HE	s ₅
D-06*8000	120-Vac control power status	d _{6,8000}	
	K15 fan control relay		k ₁₅
	S2 panel control switch:		
	Remote		c _r
	Off		c _o
	Local		c _l
	TDR1 pump 1 time delay relay		r ₁
	TDR2 pump 2 time delay relay		r ₂
	S ₁₀ pump alternating disable switch		s ₁₀
	K9 pump alternating relay:		
	Pump 1		t ₁
	Pump 2		t ₂
	K14 fan alternating relay:		
	Fan 1		t ₁
	Fan 2		t ₂

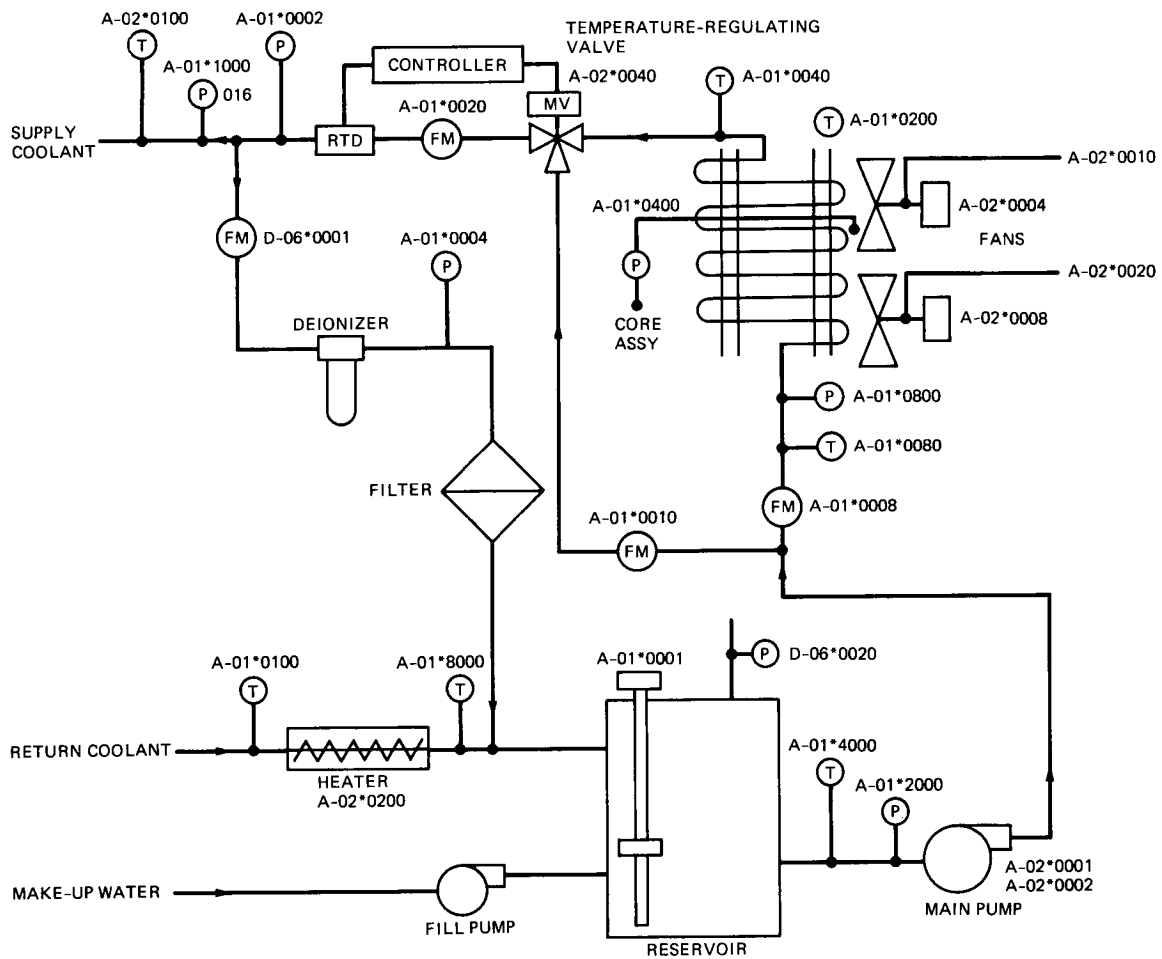


Fig. 1. Heat exchanger flow diagram



Appendix

Logic Symbol Definitions

The symbols used in the description of the operation of the assemblies of the transmitter were taken from [4]. They are described below.

Negation. A bar above a letter represents negation of the statement that this letter represents. For example, \bar{p} means "not-p" or $\neg p$. The meaning of negation is summed up in "the negation of a true statement is false; the negation of a false statement is true."

Conjunction. The conjunction of two statements such as p and q is represented as pq . The meaning of conjunction is taken to mean "a conjunction of statements all of which are true is true, and a conjunction of statements not all of which are true is false."

Alternation. The alternation of two statements such as p or q is represented as $p \vee q$. The meaning of alternation is given by this rule: "An alternation is true if at least one of the components is true and otherwise false."

Conditional. A statement of the form "if p then q" is represented as $p \longrightarrow q$ and is called a conditional. The "p" component is called the antecedent and the "q" component is called the consequent. Note that the antecedent is not to be interpreted to be the cause of the consequent. If the antecedent is false, the conditional is taken as true regardless of whether the consequent is true or false. The relation is "if p then q" and "if q then p." It is represented as $p \longleftrightarrow q$ and is called biconditional.

Grouping. The dot convention is used in place of brackets. The insertion of a dot indicates a greater break at the point where it is inserted. For example, " $pq \vee r$ " is understood to mean " $(pq) \vee r$." If the intent is " $p(q \vee r)$," the representation is " $p.q \vee r$," indicating the break between "p and q." Greater emphasis is indicated by the use of multiple dots such as ":", ":", ":", etc.

Consistency and validity. A schema is called consistent if it comes out true under some interpretation of its letters. A schema is valid if it is true under every interpretation of its letters.